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Nonlinear damped vibrations of a hybrid laminated composite plate subjected to blast load

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Abstract

In this study, the nonlinear dynamic response of a hybrid laminated composite plate composed of basalt, Kevlar/epoxy and E-glass/epoxy under the blast load with damping effects has been investigated. The von Kármán type of geometric nonlinearities are taken into account and the rectangular composite plate is assumed to be simply supported on all edges. The Galerkin Method is used to obtain the nonlinear differential equations in the time domain, and those equations are solved by Finite Difference Method. Parametric studies are conducted. The influences of some parameters such as damping ratios, aspect ratios and different peak pressure values have been investigated.

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1. Introduction

Hybrid laminated composite plates can offer better mechanical properties than conventional composite plates composed of same materials. Hybrid composite plates will become more favorite structural materials due to their high performance in order to use in various engineering applications such as space station structures, aircraft, automobiles and submarines. In order to investigate the dynamic behavior of hybrid composite plates, there are some studies in the literature. Şenyer and Kazancı [1] presented an analytical tool for the nonlinear dynamic behavior of hybrid laminated composite plates under several dynamic loads. Chen et al. [2] have investigated the dynamic

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stability of laminated hybrid composite plates subjected to periodic uniaxial stress and bending stress. Taheri-Behrooz et al. [3] have studied the design process of a shape memory alloy wire-reinforced hybrid composite (SMAHC) plate. Hawng and Mao [4] have studied the buckling loads, delamination growth loads, and failures of delaminated interply hybrid composite plates under compression stress. Topdar et al. [5] have investigated the free vibration characteristics of laminated composite and sandwich plates with embedded and/or surface-bonded piezoelectric layers. They have proposed a hybrid plate theory for modeling the structural system. Shokuhfar et al. [6] have developed the analytical and a mathematical model in order to show the effect of low-velocity impact upon the smart hybrid composite structure. They have also studied the effect of some parameters such as the volume fraction, the orientation and the through thickness location of the SMA wires, on impact response of the smart hybrid composite plate. Muñoz et al. [7] have investigated the deformation and failure micro-mechanisms of a hybrid 3D woven composite in tension. Chen et al. [8] have performed the thermal buckling analysis on hybrid functionally graded plates (FGPs) with an arbitrary initial stress. Le Maoût et al. [9] have proposed a complete optimization procedure in order to determine simultaneously the optimal number and locations of hybrid elastomer and composite sandwich plates. Naik et al. [10] have investigated the impact behavior and post impact compressive characteristics of glass–carbon/epoxy hybrid composites with alternate stacking sequences. Ary Subagia et al. [11] have studied the effect of different stacking sequences of carbon and basalt fabrics on the flexural properties of hybrid composite laminates.

There are also some studies about the damped vibrations of the composite structures. Kazancı [12] has investigated the nonlinear dynamic response of a viscously damped sandwich plate subjected to blast load. Kim et al. [13] have studied the effect of seawater absorption on the damping and fracture behaviors of carbon nanotube (CNT)-modified epoxy/basalt fiber (basalt/CNT/epoxy) multiscale composites. Boumediene et al. [14] have developed a reduction method to determine the modal characteristics of damped viscoelastic sandwich structures. Won et al. [15] have introduced a 2-node damped beam element according to the Mead and Markus' approach in order for the DOF-efficient forced vibration analysis of three-layered symmetric straight sandwich beams with a viscoelastic core. Yang et al. [16] have investigated the vibration and damping performances of hybrid carbon fiber composite pyramidal truss sandwich panels with viscoelastic layers embedded in the face sheets. Kyriazoglou and Guild [17] have developed a hybrid methodology for the prediction of damping properties of vibrating composite laminates which could also be applied to homogeneous materials.

In this study, it is aimed to analyze the nonlinear dynamic response of hybrid laminated composite plates, composed of basalt, Kevlar/epoxy and E-glass/epoxy under the blast load including damping effects, as a more realistic approach. Basalt is used as one of the hybrid elements due to it is one of the recent promising materials for the fabrication of the advanced composites. Basalt is a natural inert material produced naturally from the volcanic rocks [18]. Composites reinforced with basalt fibers have prominent properties over the other composites such as good mechanical performance, in particular at high temperature, better impact strength and blast resistant, 17.5 percent better elastic modulus than fiberglass, considered as "green" recyclable, non-respirable and safer even in the factory, will not ignite easily with the right resins and low cost. Although basalt composites have superior properties, its possible applications has not been investigated completely yet. New basalt composite applications could be widely used in near future due to the potential of low cost of this material [19]. In addition, there are two possible effects of the blast [20]: Sudden pressure and the temperature rise. Therefore, using the basalt composites subjected to blast loads would be preferable due to their high temperature resistance. Therefore, the objective of the present paper is to investigate the nonlinear damped vibrations of simply supported hybrid laminated composite plates composed of basalt, Kevlar/epoxy and E-glass/epoxy subjected to blast load.

2. Equations of motion

A mathematical model for the hybrid laminated composite plates is presented in this section. Hybrid laminated composite plate used in this study is shown in Fig.1. The hybrid plate is composed of two basalt fabric plies, two Kevlar/epoxy plies and two E-glass/epoxy plies, respectively.

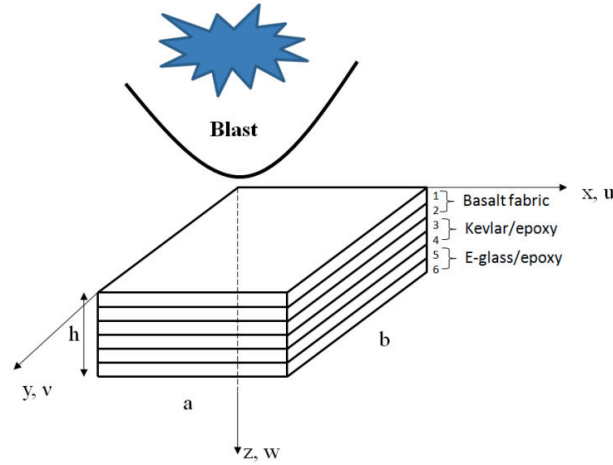


Fig. 1. Hybrid laminated composite plate.

Kazancı and Mecitoğlu [21] have derived the equations of motion of the damped vibrations of a laminated plate subjected to blast load. They have obtained the nonlinear dynamic equations of a laminated composite plate in terms of mid-plane displacements, using the constitutive equations and the strain-displacement relations in the virtual work and applying the variational principles, as follows:

$$\begin{aligned} L_{11}u^0 + L_{12}v^0 + L_{13}w^0 + N_1(w^0) + d_1\dot{u}^0 + \bar{m}\ddot{u}^0 - q_x &= 0 \\ L_{21}u^0 + L_{22}v^0 + L_{23}w^0 + N_2(w^0) + d_2\dot{v}^0 + \bar{m}\ddot{v}^0 - q_y &= 0 \\ L_{31}u^0 + L_{32}v^0 + L_{33}w^0 + N_3(u^0, v^0, w^0) + d_3\dot{w}^0 + \bar{m}\ddot{w}^0 - q_z &= 0 \end{aligned} \quad (1)$$

Here, L_{ij} and N_i are linear and nonlinear operators. \bar{m} is the mass of unit area of the mid-plane, where q_x , q_y and q_z are the load vectors in the axes directions, while d_1 , d_2 and d_3 denote the viscous damping coefficients in the x, y and z directions, respectively. The explicit expressions of the operators can be found at the Appendix of [21] and [22]. The boundary conditions are considered as all edges are simply supported and given as:

$$\begin{aligned} u^0(0, y, t) = u^0(a, y, t) = u^0(x, 0, t) = u^0(x, b, t) &= 0 \\ v^0(0, y, t) = v^0(a, y, t) = v^0(x, 0, t) = v^0(x, b, t) &= 0 \\ w^0(0, y, t) = w^0(a, y, t) = w^0(x, 0, t) = w^0(x, b, t) &= 0 \end{aligned} \quad (2)$$

$$M_x = 0 \text{ at } x = 0, a$$

$$M_y = 0 \text{ at } y = 0, b \quad (3)$$

and initial conditions are given by

$$\begin{aligned} u^0(x, y, 0) = 0, \quad v^0(x, y, 0) = 0, \quad w^0(x, y, 0) = 0, \\ \dot{u}^0(x, y, 0) = 0, \quad \dot{v}^0(x, y, 0) = 0, \quad \dot{w}^0(x, y, 0) = 0 \end{aligned} \quad (4)$$

If the blast source is distant enough from the plate, the blast pressure can be described in terms of the Friedlander exponential decay equation as

$$P(t) = P_m \left(1 - \frac{t}{t_p}\right) e^{-\alpha t/t_p} \quad (5)$$

where the negative phase of the blast is included. Here P_m is peak pressure, t_p is positive phase duration and α is waveform parameter (Fig.2).

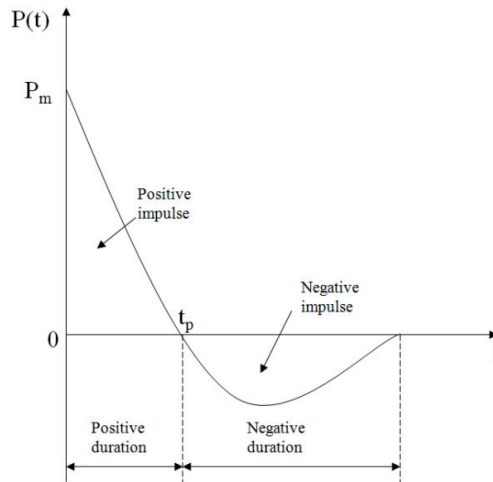


Fig. 2. Exponential blast loading.

3. Numerical results

The dimensions of the hybrid composite plate given in Fig.1 are taken as $a=b=0.22$ m and $h=2.1(10^{-3})$ m. The ply material properties are given in Table 1.

Table 1. Properties of basalt, Kevlar/epoxy and E-glass/epoxy

Material	Modulus of Elasticity ($E_1=E_2$) (GPa)	Shear Modulus G_{12} (GPa)	Poisson's ratio ν	Density ρ (kg/m ³)	Ply thickness (mm)
Basalt fabric	25	4	0.086	2800	0.35
Kevlar/epoxy	87	2.2	0.34	1380	0.35
E-glass/epoxy	39	3.8	0.28	2100	0.35

The analyses are performed for the uniform blast pressure. The maximum blast pressure (P_m) is taken to be 29 kPa for the plate and all edges are simply supported. The other parameters of the Friedländer function given in Eq. (5) are chosen as $\alpha = 0.35$ and $t_p = 0.0018$ s.

Fig.3 shows the dynamic vibration responses of undamped plate and the plate with viscous damping ratio ξ ($= d_2/2\omega\bar{m}$) taken as 0.3. As expected the plate will be damped rapidly and the vibration frequency is increased.

If we consider different viscous damping ratios such as 0.1, 0.2, and 0.3, the results appear as in Fig.4. As can be seen from the Fig.4, the vibration frequency increases with increasing the damping ratio and in contrast, the deflection amplitude decreases, as expected.

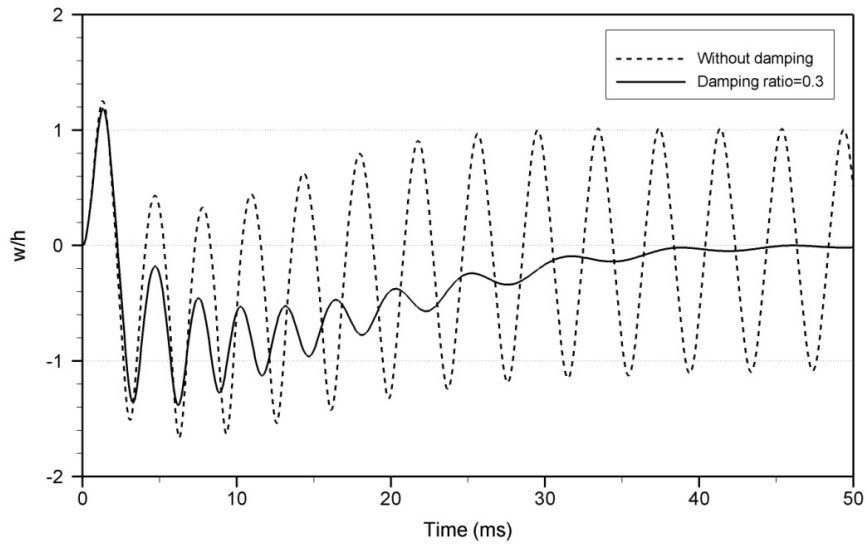


Fig. 3. Comparison of dimensionless deflection of damped and undamped plates.

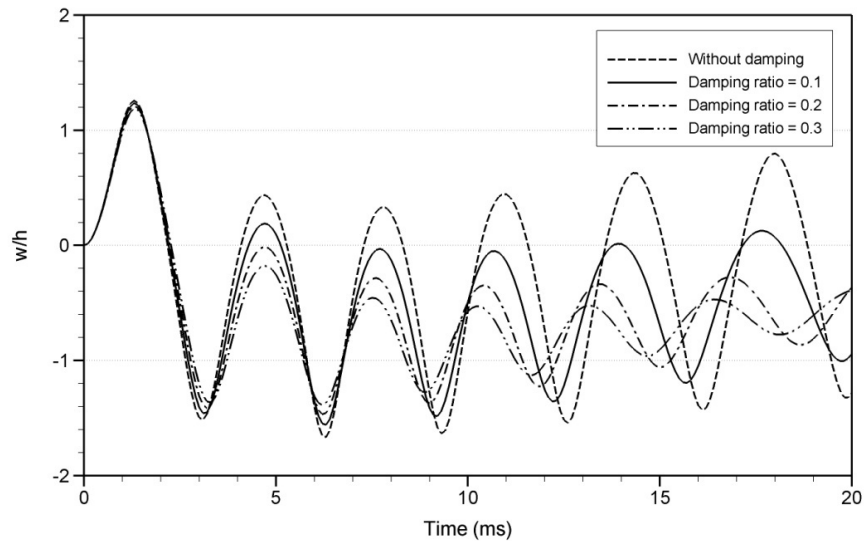


Fig. 4. Comparison of different viscous damping ratios.

Fig. 5 shows the displacement time histories for the various aspect ratios of the hybrid composite plate while $P_m=29$ kPa and viscous damping ratio is 0.1. The mid-plane area of the plate is preserved as a constant value for all

the aspect ratios. The peak deflection of the plate exponentially decreases while the aspect ratio decreases. Figure 5 also shows that the vibration frequency increases with the decreasing aspect ratio.

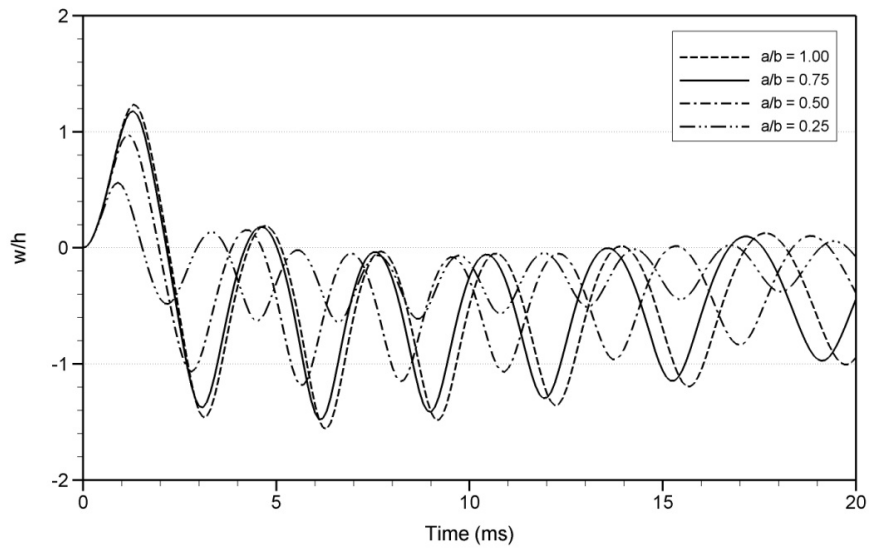


Fig. 5. Effect of different aspect ratios (damping ratio=0.1).

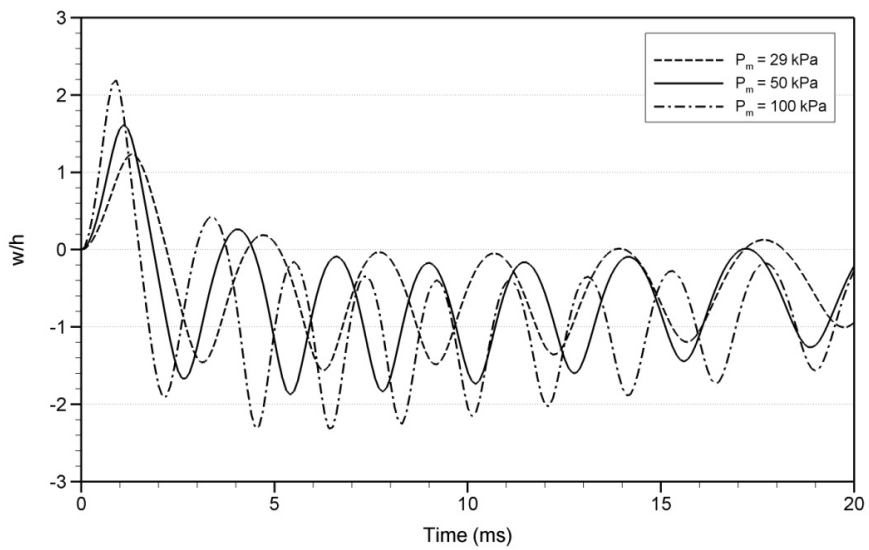


Fig. 6. The center dimensionless deflection time histories for various peak pressure values (damping ratio=0.1).

The effects of different peak pressure values could be seen in Fig.6. The viscous damping ratio is taken to be 0.1 and dimensions are $a=b=0.22$ m for these analyses. The deflection amplitude and the vibration frequencies increase while increasing the peak pressure value, as expected.

4. Conclusions

In this study, the nonlinear dynamic response of a hybrid laminated woven composite plate, composed of basalt fabric, Kevlar/epoxy and E-glass/epoxy under the blast load including damping effect has been investigated. Basalt fabric is chosen as outer layer of the plate to avoid the temperature effect of the blast wave.

Some parametric studies are conducted for the hybrid laminated composite plate subjected to blast load, considering the influences of some parameters such as damping ratios, aspect ratios and different peak pressure values. The amplitude of the damping ratio plays a major role on the deflection of the plate and the frequencies. The damping effects decrease the vibration amplitude in a short time. The frequency of vibration is decreased by the structural damping effects slightly, as expected. The vibration frequency increases with increasing the damping ratio and in contrast, the deflection amplitude decreases.

While the aspect ratio of the hybrid plate decreases, the deflection amplitude of the plate decreases, and the corresponding frequency increases. Different peak pressure values are applied to the hybrid plate in order to show its effect. It is found that the deflection amplitude and the vibration frequencies increase while increasing the peak pressure value.

In this study, only one term is taken for the each displacement function. Therefore, the contributions of the higher modes to the structural response are not included.

A study can be performed for different boundary conditions, geometries and materials with the temperature dependent material properties. This can be the subject of future work.

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